Error Correction using NV-center

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Why quantum error correction?

Decoherence from interacting with environment

Can have faulty gates or preparation

Errors are continuous (sign/bit flip)

Outline

Classical Error Correction

Quantum Error Correction

Experimental Setup (NV-center)

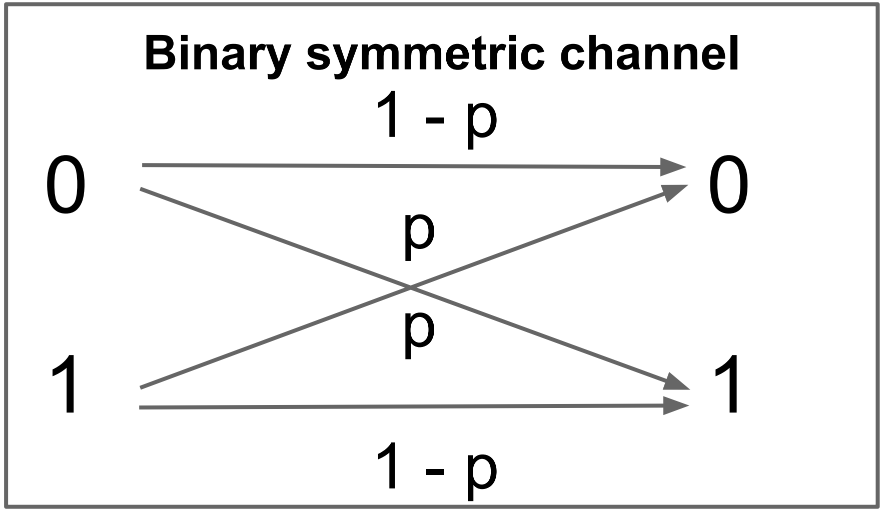
Results and conclusions

Classical Error Correction

Classical error correction

1. Encode by copying
   $0 \rightarrow 000$
   $1 \rightarrow 111$
2. Decode by majority voting

Improvement for error probability $p<\frac{1}{2}$



Quantum Error Correction

Quantum error correction (QEC)

1. No cloning theorem

2. Measurement destroys quantum information

3. Error are continuous

QEC: Bit flip error - encoding

One intuitive approach

$a|0\rangle + b|1\rangle \rightarrow a|000\rangle + b|111\rangle$

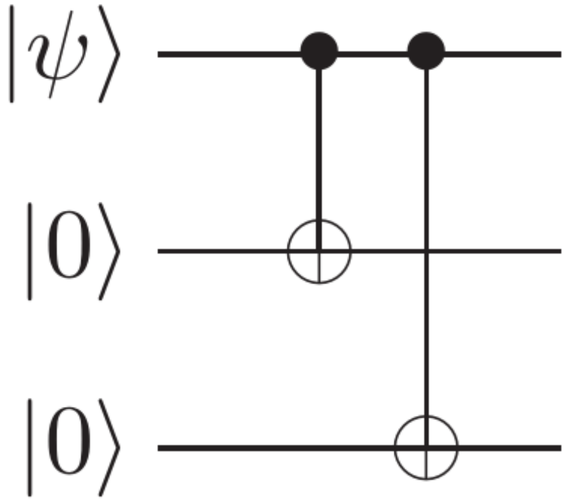
Logical states

$|0_L\rangle \equiv |000\rangle$

$|1_L\rangle \equiv |111\rangle$

Suitable for bit flip QEC

E.g. $a|100\rangle + b|011\rangle$



QEC: Bit flip error - detection

Z_1Z_2 - Check parity of qubits 1 and 2

Operator: $Z \otimes Z \otimes I$

+1 if same, -1 if different

$a|100\rangle + b|011\rangle$

Do same for 2,3 → we can determine if a bit flip occurred

No information about amplitudes, a and b, thus the superposition is not destroyed

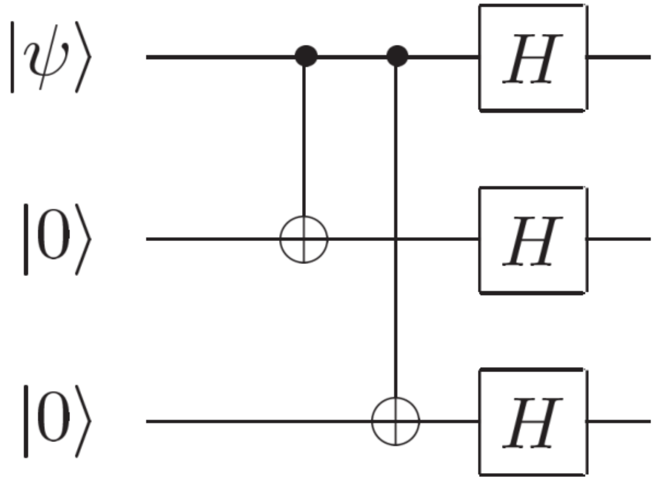
QEC: Phase error - encoding

Like Bit flip but use |+> and |–> states

$|0_L\rangle \equiv |{+}{+}{+}\rangle$

$|1_L\rangle \equiv |{-}{-}{-}\rangle$

Encode using Hadamard gates

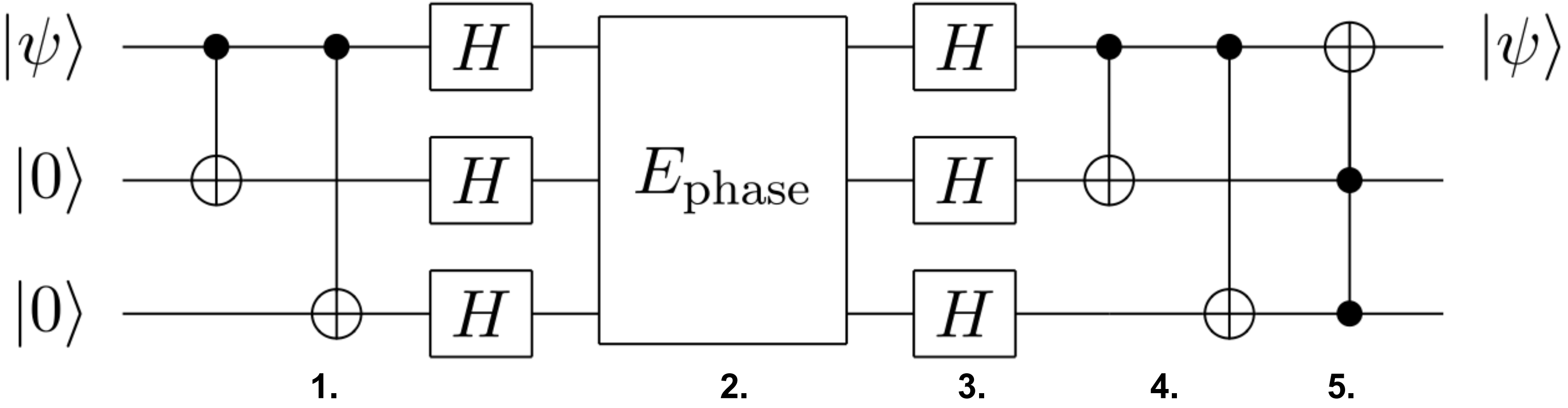


New operators

$H^{\otimes 3} Z_1 Z_2 H^{\otimes 3} = X_1 X_2$

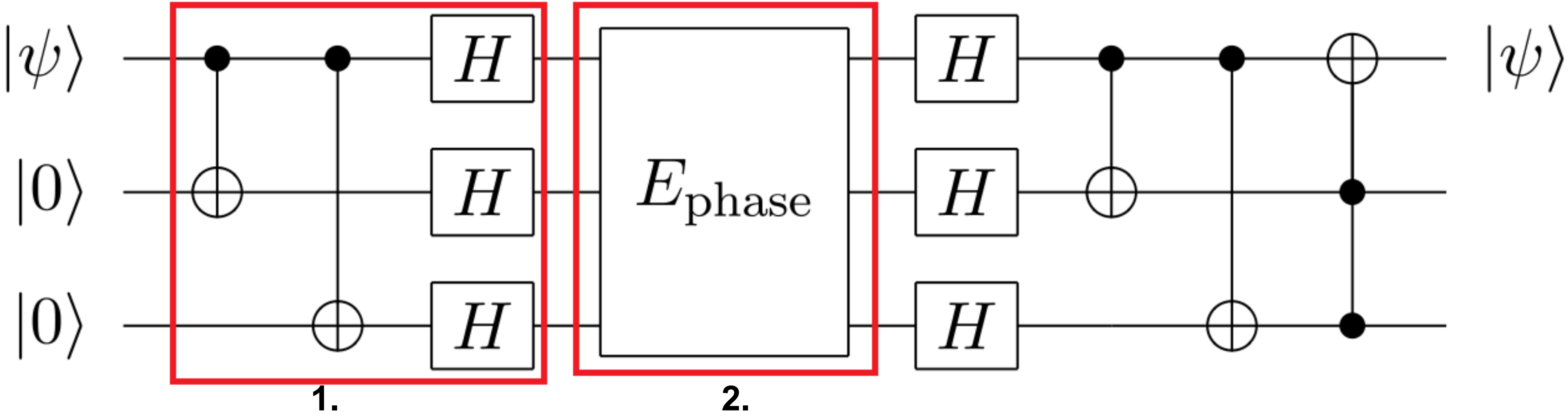
$H^{\otimes 3} Z_2 Z_3 H^{\otimes 3} = X_2 X_3$

QEC: Phase error - implementation



1. Encode
2. Phase error
3. Decode
4. Detect
5. Restore

QEC: Phase error - implementation

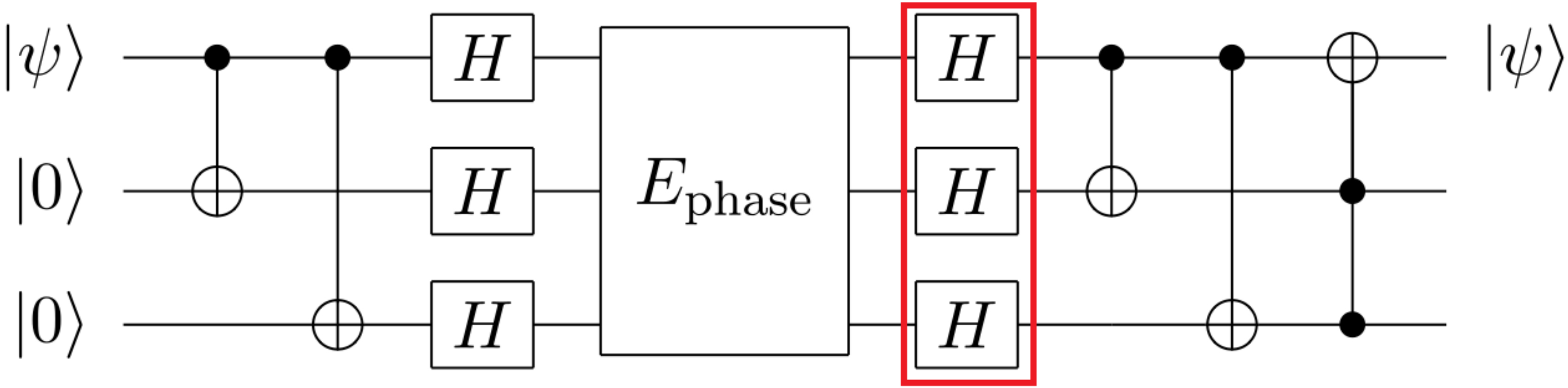


1. **Encode**

   a|0> + b|1> → a|+++> + b|- - ->

2. **Phase error**

QEC: Phase error - implementation

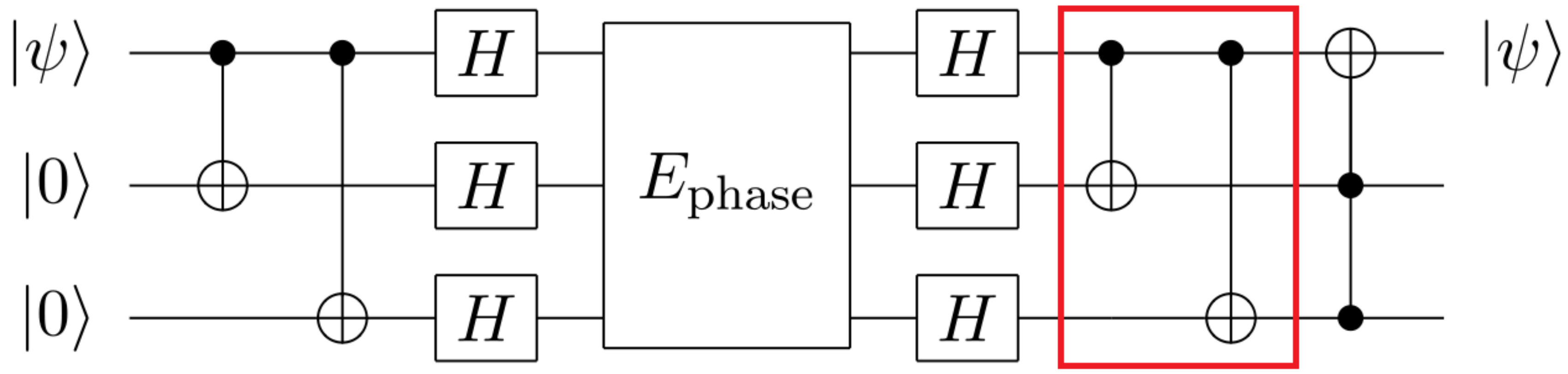


3. **Decode**

No error: a|000> + b|111>

Error: a|100> + b|011>

QEC: Phase error - implementation

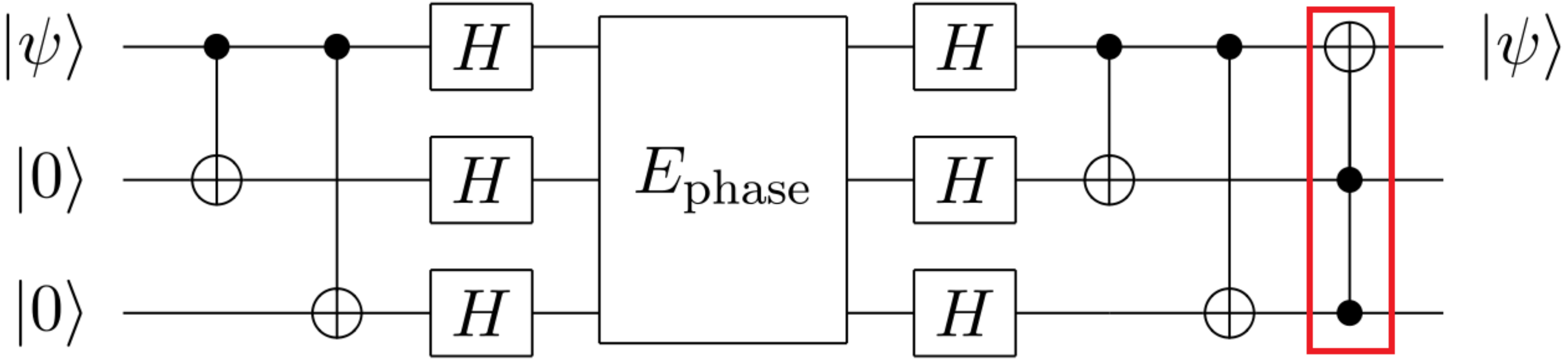


4. **Detect**

No error: a|000> + b|111> → (a|0> + b|1>)⊗|00>

Error: a|100> + b|011> → (a|1> + b|0>)⊗|11>

QEC: Phase error - implementation



5. **Restore**

   No error: (a|0> + b|1>)⊗|00> → (a|0> + b|1>)⊗|00>

   Error: (a|1> + b|0>)⊗|11> → (a|0> + b|1>)⊗|11>

QEC: Summary

1. No cloning theorem

   No cloning necessary!
2. Measurement destroys quantum information

   Amplitudes a and b not measured!
3. Error are continuous

   Correction of bit flip and phase errors sufficient!

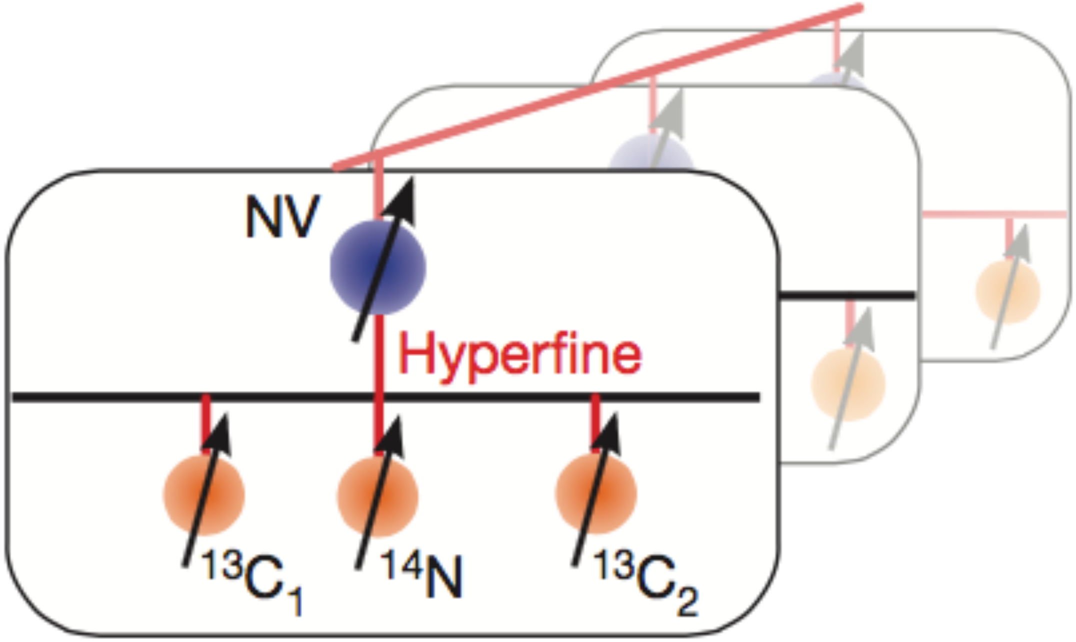
Experimental Setup

Setup: Nitrogen Vacancy (NV) center

A hybrid spin system

$^{13}C_1$, $^{13}C_2$ and ^{14}N used as Qubits'

Electron spin is used for read out and initialization

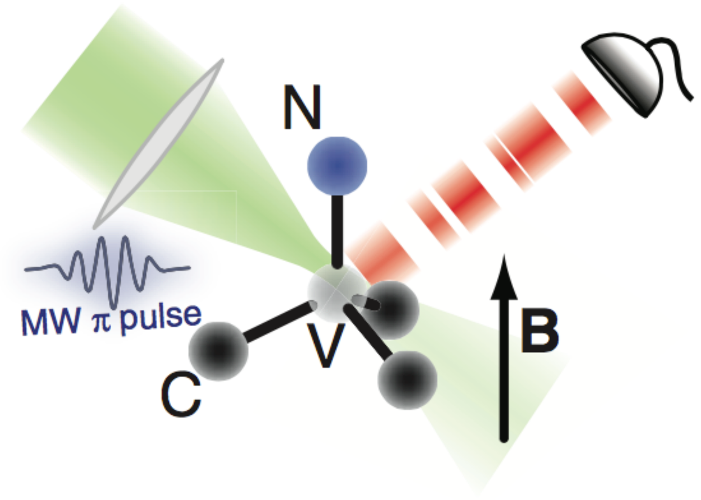


G. Waldherr et al., Nature, 2014/01/29/online

Setup: Spin manipulation

- Electron and nuclear spins are manipulated by microwave signals

- Which rotates the spins around an axis in the x–y plane of the Bloch sphere.



P. Neumann et al., Science, 2010/06/30, Vol 329

Setup: Hyperfine splitting

Hyperfine splitting

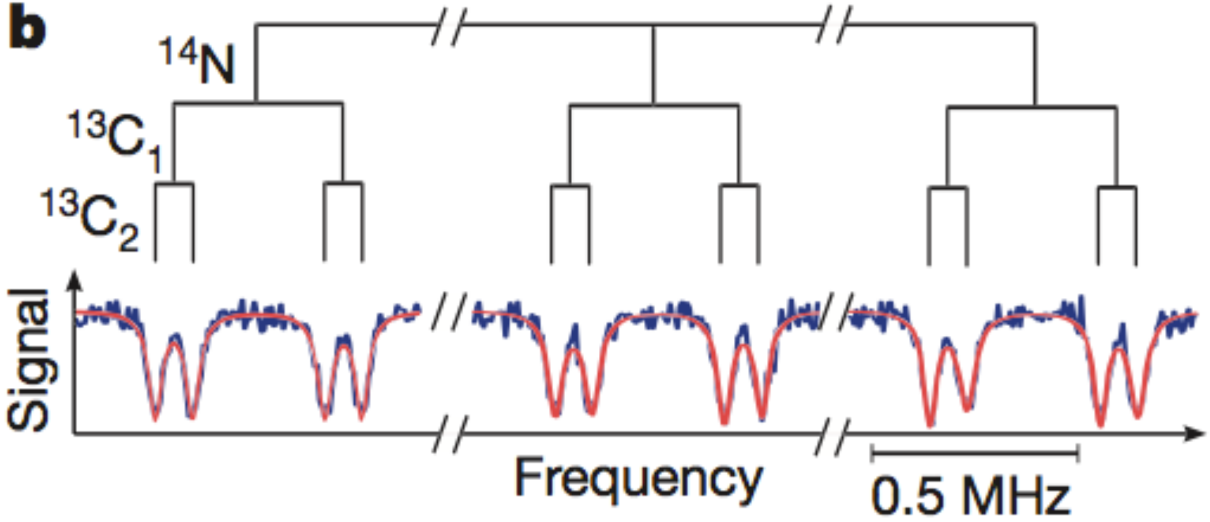
electron: $m_s = 0 \rightarrow -1$

- ^{14}N: 2,16 MHz
- $^{13}C_1$: 413 kHz
- $^{13}C_2$:89 kHz

As Qubits use:

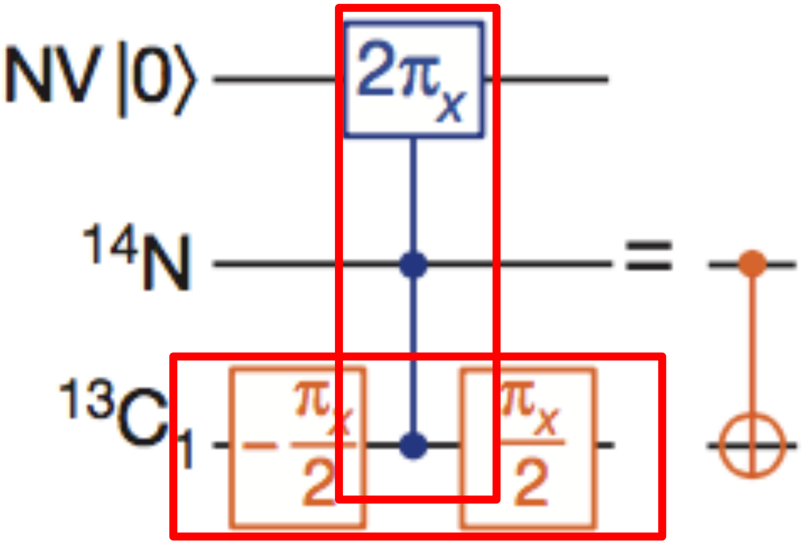
N: m_I = 0, -1 as |0>
and +1 as |1>

$C_{1,2}$: $m_I = \pm 1/2$



G. Waldherr et al., Nature, 2014/01/29/online

Setup: CNOT gate



CNOT gate between two nuclear spins

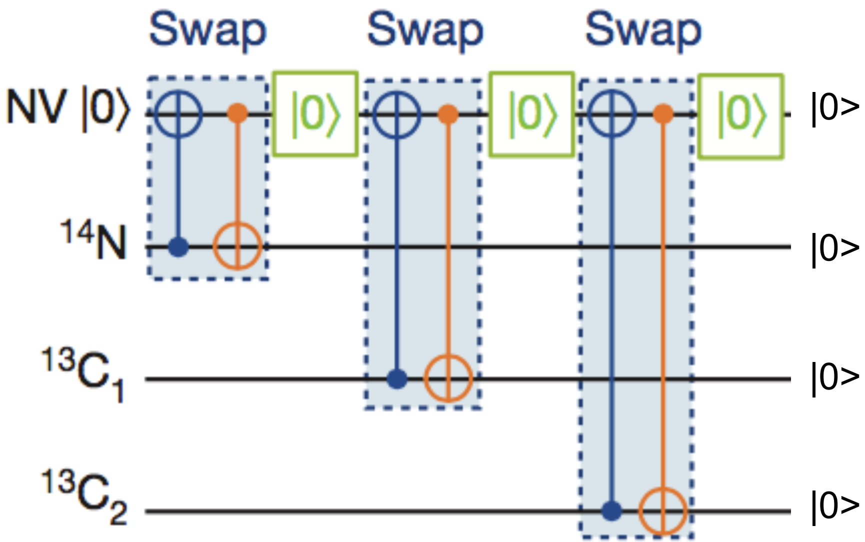
CPhase

Hadamard rotations

G. Waldherr et al., Nature, 2014/01/29/online

Setup: SWAP gate

SWAP-like gates are used to transfer electron spin polarization onto the nuclear spins



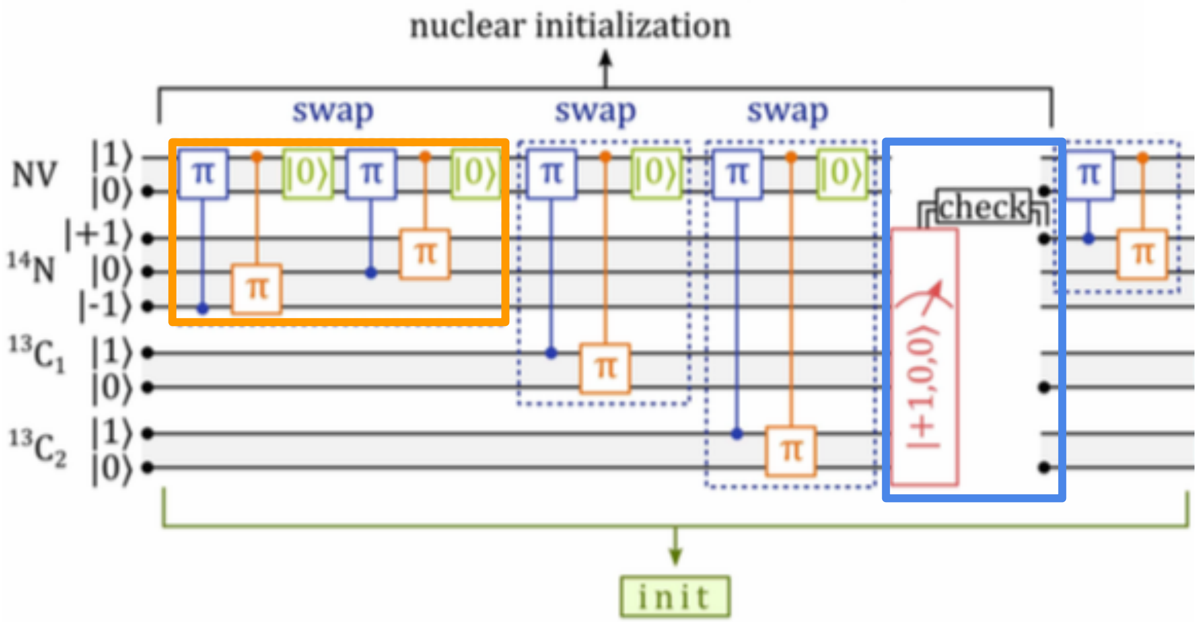
G. Waldherr et al., Nature, 2014/01/29/online

Setup: Initialization

To raise initialization fidelity:

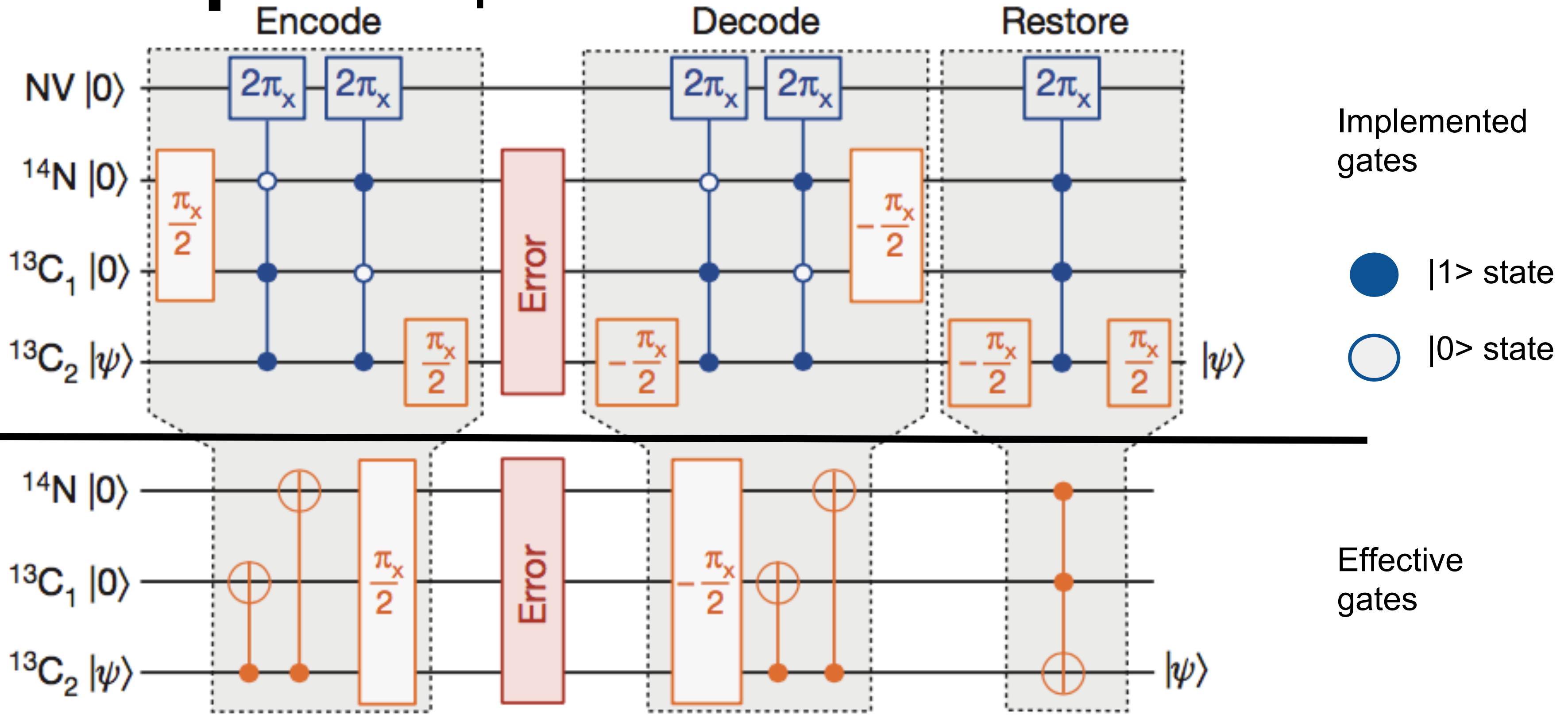
- Address issue with charge state of the NV
- Discard if N is still in m_I = +1 state

99% initialization fidelity can be achieved for the state $|^{14}N, ^{13}C_1, ^{13}C_2 = |0, 0, 0>$



G. Waldherr et al., Nature, 2014/01/29/online

Setup - The phase QEC



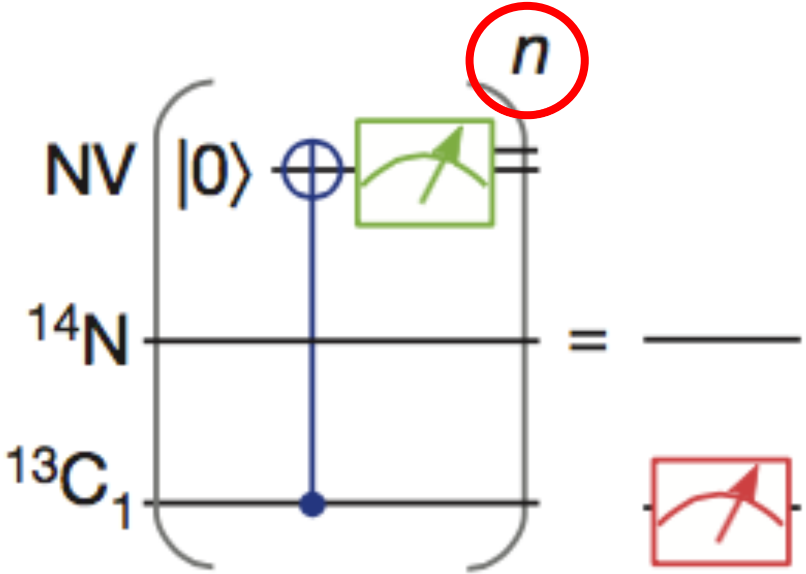
G. Waldherr et al., Nature, 2014/01/29/online

Setup: Projective read out

Projective read out of
$^{13}C_1$ nuclear spin.

Repeatable

Readout fidelities:
^{14}N : 95.8%
$^{13}C_1$: 96.9%
$^{13}C_2$: 99.6%

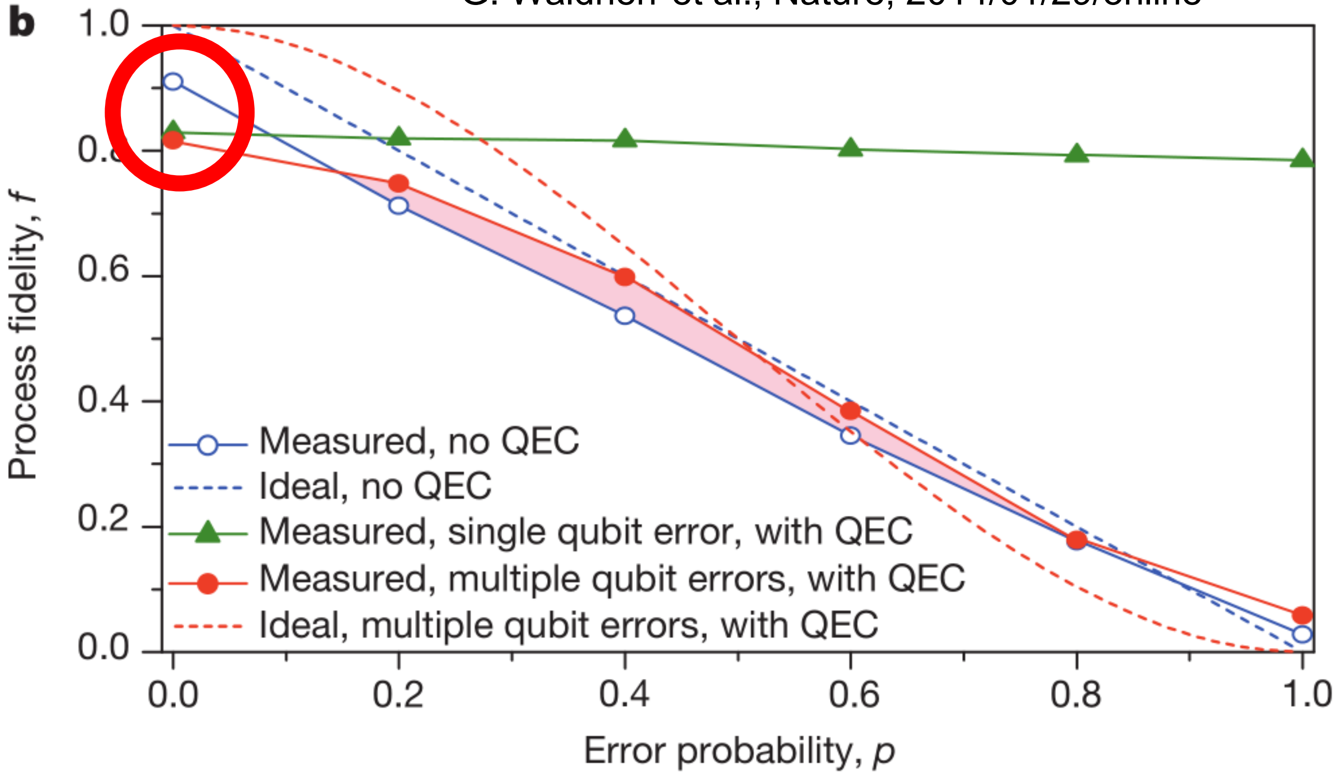


G. Waldherr et al., Nature, 2014/01/29/online

Results

Results: Process fidelity on error probability

G. Waldherr et al., Nature, 2014/01/29/online



Conclusions

NV-center vs Superconducting

NV-center:

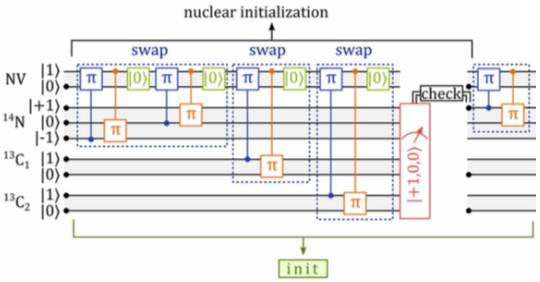
- Strong coupling - up to 10 qubits possible
- Room temperature

Superconducting:

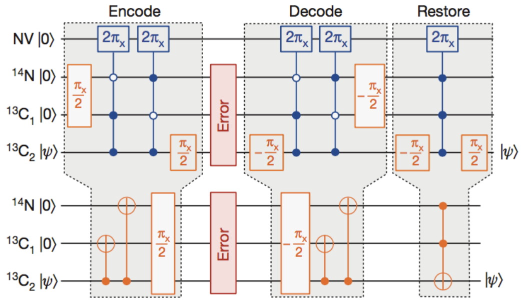
- 5 to 9 qubits working QEC
- mK temperatures

Conclusions

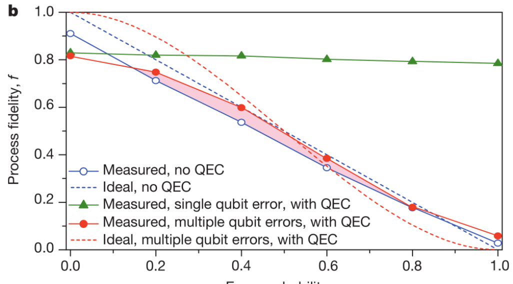
High-fidelity initialization of a whole spin register (99 %)



Implementation of Phase QEC



Corrects multiple qubit phase errors



Acknowledgement and references

Thanks to Dr. Abdufarrukh Abdumalikov for helpful supervising!

[1] G. Waldherr et al., Nature, 2014/01/29/online

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[5] M. Nielsen, I. Chuang, Quantum Computation and Quantum Information, 2010